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ON THERMAL STRESS MEASUREMENT FOR
TWO TYPES OF ELEVATED TEMPERATURE STRAIN GAGES

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INTRODUCTION

Several resistance strain gages are available for use at elevated temperatures. Strain data measured while the sensor is at elevated temperature is prone to contain apparent strain. Ideally, a batch of strain gages can be corrected for apparent strain using a single apparent strain result for the entire batch. This paper presents the results of laboratory tests which examines apparent strain consistency within the batch for two types of sensors intended for use at elevated temperatures. The implications of the apparent strain study are extended to include thermal stress measurements.

A bonded foil type of strain gage (intended for use up to 533 K (500°F)) and a weldable type strain gage (intended for use up to 755 K (900°F)) were selected for the study. Two separate experiments were conducted. Both types of strain sensors were mounted on a built-up structure which was heated non-uniformly to produce thermal stress. Both types of strain sensors were also mounted on coupons and heated uniformly to generate apparent strain information. A significant sampling of strain gages was used on both the built-up structure heating tests and the coupon heating tests so that statistically relevant data resulted. The results obtained from both sensors were compared within their common temperature range. The two experiments encompass a broad spectrum of information pertinent to intra-batch apparent strain consistencies and to computation of thermal stresses from strain data.

SYMBOLS

D	deviation from the mean
D_{\max}	maximum deviation from the mean
N	total number of discrete measurements
x_j	j^{th} discrete element
\bar{x}	arithmetic mean

INSTRUMENTATION AND TEST PROCEDURES

Built-up Structure Heating Test

An all titanium built-up structure (see figure 1) was installed with numerous strain gages arranged in equiangular rosettes. Weldable strain gages and foil strain gages were installed concentrically as shown in figure 2. The skin of this test structure was heated from the far side (figure 1) up to 533 K (500°F) to create a thermal stress resulting from this non-uniform heating. The purpose of this experiment is to provide comparable strain gage rosette data for both types of strain gages from which evidence of apparent strain anomalies can be detected.

The test structure shown in figure 1 is fabricated entirely of 6Al-4V titanium. The length of the specimen is 2.44 meters (96.0 inches). The .0063 meter (.25 inch) skin is attached to four .0013 meter (.050 inch) thick zee-shaped spars using mechanical fasteners. A .0114 meter (.45 inch) lower cap is attached to the bottom of the zee-shaped spars with mechanical fasteners. A more detailed description of the test structure may be found in reference 1.

The heating test plan included heating the skin on the side away from the spars using radiant heaters. The lower part of the structure was shielded from radiant heat. The skin was heated to 533 K (500°F) from room temperature and held at that temperature.

Coupon Heating Test

A total of sixteen elevated temperature strain gages (eight bonded foil and eight weldable) were mounted on two titanium (6Al-4V) coupons .089 meter (3.5 inch) by .140 meter (5.5 inch) by .0064 meter (.25 inch) thick. One of the coupons, the strain sensors, and the installation is shown in figure 3. Two strain gages of each type

are mounted on each side of the coupon. The foil strain gages were bonded to the coupon with an epoxy type cement. The cemented strain gages were cured under pressure at a temperature of 394 K (250°F) for 2.5 hours. The weldable strain gages were attached by spot welding the flanges of the sensor to the coupon. The flange and the casing of the weldable strain gages were constructed of Rene 41 material.

A photograph of the heating fixture with one of the strain gaged coupons mounted inside is presented in figure 4. The coupon is positioned horizontally so that radiant heaters provide heat from above and below. Temperatures are monitored and controlled by thermocouples located on the upper and lower surfaces of the coupon. The basic test procedure was to heat the specimen uniformly to a predetermined temperature, maintain the temperature at that value for five minutes, and then heat the specimen to some higher predetermined temperature. This procedure was repeated until the maximum desired temperature was achieved. The heat was then terminated and the specimen was allowed to cool.

RESULTS

Apparent Strain Tests

The apparent strain tests were conducted in two sets. The first set involved heating the coupons in steps up to 533 K (500°F) four times. Data from all four tests were recorded and will be presented. The second set involved heating the coupons in steps up to 755 K (900°F) four times. Only the weldable strain gages were recorded during the second set of tests since the temperatures above 533 K (500°F) permanently damaged foil gages to the extent that they were no longer usable.

Foil Strain Gages.— The results of the apparent strain tests are presented for the foil strain gages in figures 5(a) and 5(b). Strain data were taken at four increments: (1) the initial room temperature strain, (2) the strain after the coupon temperature was held at 422 K (300°F) for five minutes, (3) the strain after the coupon temperature was held at 533 K (500°F) for five minutes, and (4) the residual strain (due to hysteresis) after the coupon was returned to room temperature.

The foil strain gages consistently exhibited no significant hysteresis after the first test cycle. Hence, only the hysteresis value for the first cycle is presented in figure 5. The symbols represent the test data and the solid line represents the manufacturers apparent strain curve for the batch of strain gages tested. It can be seen that after the first cycle hysteresis, the apparent strain measured during the tests correlates well with the manufacturers predicted values.

Weldable Strain Gages.- The results of the apparent strain tests are presented for the weldable strain gages in figures 6(a) through 6(d). Data was taken at six increments: (1) the initial room temperature strain, (2) the strain after the coupon was held at 422 K (300°F) for five minutes, (3) the strain after the coupon temperature was held at 533 K (500°F) for five minutes, (4) the strain after the coupon temperature was held at 644 K (700°F) for five minutes, (5) the strain after the coupon temperature was held at 755 K (900°F) for five minutes, and (6) the residual strain (due to hysteresis) after the coupon had returned to room temperature. No apparent strain curve was provided for these strain gages by the manufacturer.

The weldable strain gages consistently exhibited negligible hysteresis after the second cycle. Hence, only the hysteresis values for the first and second cycles are shown in figure 6. One of the eight weldable strain gages failed during the test, hence, only data for seven strain gages is presented in figure 6. It can be seen that considerable variation has occurred in the apparent strain of the seven sensors.

Statistical Evaluation.- The foil strain gages exhibited little variation in apparent strain among the eight sensors tested. The apparent strain variation with temperature corresponded closely to the manufacturers prediction. Large variations in apparent strain were observed among the seven weldable strain gages. These variations warranted a statistical evaluation to achieve a functional apparent strain curve for the weldable strain gages and to compare the two types of strain gages.

A statistical presentation of the apparent strain of the foil and weldable strain gages is shown in figures 7 and 8, respectively. The test data, the arithmetic mean,

$$\bar{x} = \frac{\sum_{j=1}^{j=N} x_j}{N} \quad (1)$$

the mean deviation,

$$D = \frac{\sum_{j=1}^{j=N} |x_j - \bar{x}|}{N} \quad (2)$$

and, the maximum deviation,

$$D_{\max} = (x_j - \bar{x})_{\max} \quad (3)$$

are presented for comparison purposes.

Built-up Structure Tests

Principal Stresses.- An example of a major problem resulting from the combination of uncertain apparent strain information and low level thermal stress can be seen in the equiangular rosette data of figures 9 and 10. This data results from the built-up structure heating test described in the Instrumentation and Test Procedures Section. The time-histories in figure 9 are the A, B, and C legs of a concentrically configured pair of rosettes. The outer rosette is made up of weldable strain gages and the inner rosette is made up of foil strain gages. Also shown is a time-history of temperature at the rosette location. The strains measured with the foil strain gages are corrected for apparent strain using the manufacturers apparent strain data. The strains measured with the weldable strain gages are corrected for apparent strain using the arithmetic mean of the data presented in figure 8.

The apparent strain data supplied by the manufacturer of the foil gages was shown to be consistent with very little scatter. Hence, the strain measured with the foil strain gages in figure 9 are considered very close to the true value. It can be easily seen in figure 9 that the strains measured with the weldable strain gages and corrected with the apparent strain data of figure 8 do not correlate with the strains measured with the foil strain gages. This discrepancy can have dramatic results when the principal stresses and the angles to principal stresses are calculated using the data reduction methods developed in reference 2 for equiangular rosettes. The comparison shown in figure 10 demonstrates that uncertain apparent strain corrections can have dramatic effects on the results of rosette data when relatively small thermal stresses are being measured.

Gage Factor Changes.- The data presented in reference 3 clearly shows that the gage factor for weldable strain gages undergoes a measureable change for elevated temperatures. The effect of the change is indicated to average one to two percent per 56°K (100°F) of elevated temperature, hence, the gage factor change is not the major factor in the low level thermal stress being examined in this paper. At large levels of measured strain, gage factor corrections are major considerations whereas apparent strain corrections tend to occupy a minor role.

DISCUSSION

The basic purpose of this paper is to examine a weldable type strain gage used to measure low level thermal stress in a temperature environment up to 755 K (900°F). The method involved using foil strain gages with well identified characteristics as a standard of comparison up to 533 K (500°F). This latter temperature (533 K

(500°F) represents the upper usable limit of the foil strain gages.

The data presented in the Results Section identified a basic problem in that a significant variation in apparent strain characteristics existed among the weldable strain gages. Attempts to measure low level thermal stresses with these weldable strain gages proved difficult because of the large scatter among apparent strain data for the weldable strain gages (figure 8). A clamping device reported in reference 3 shows promise of providing a method of determining apparent strain characteristics prior to installation. The problems with apparent strain characteristics of low level measurements diminish as larger stresses are encountered. Gage factor changes tend to become a dominate factor in the accuracy of large stress measurements.

A general apparent strain curve was established by running coupon tests on a number of weldable strain gages from the batch. A mean value for apparent strain was determined at various temperatures. The scatter of the apparent strain data among the weldable strain gages was too large to effectively correct the gages for apparent strain from information deduced from a sampling of the batch. Individual apparent strain information must be acquired prior to installation for this type of weldable strain gage.

CONCLUDING REMARKS

A weldable type strain gage was used to measure low level thermal stress in an elevated temperature environment. Foil strain gages used in a comparative manner revealed that the apparent strain of the weldable strain gages was not sufficiently known to acquire accurate low level thermal stress data. Apparent strain data acquired from coupon tests revealed a large scatter in apparent strain characteristics among the weldable strain gages.

It was concluded that apparent strain data for each individual weldable strain gage must be acquired prior to installation if valid thermal stress data is to be obtained through the temperature range of room temperature to 755 K (900°F).

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December 9, 1982*

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2. Marin, Joseph; and Sauer, John A.: Strength of Materials. Second Edition, The Macmillon Company, New York.
3. Nightingale, C. M.; and Twa, G. J.: Evaluation of Precalibration Techniques for Ailtech SG425 Strain Gages. Society for Experimental Stress Analysis. Western Regional Strain Gage Committee Meeting, Feb. 16, 1982.



Figure 1. Titanium Test Specimen.

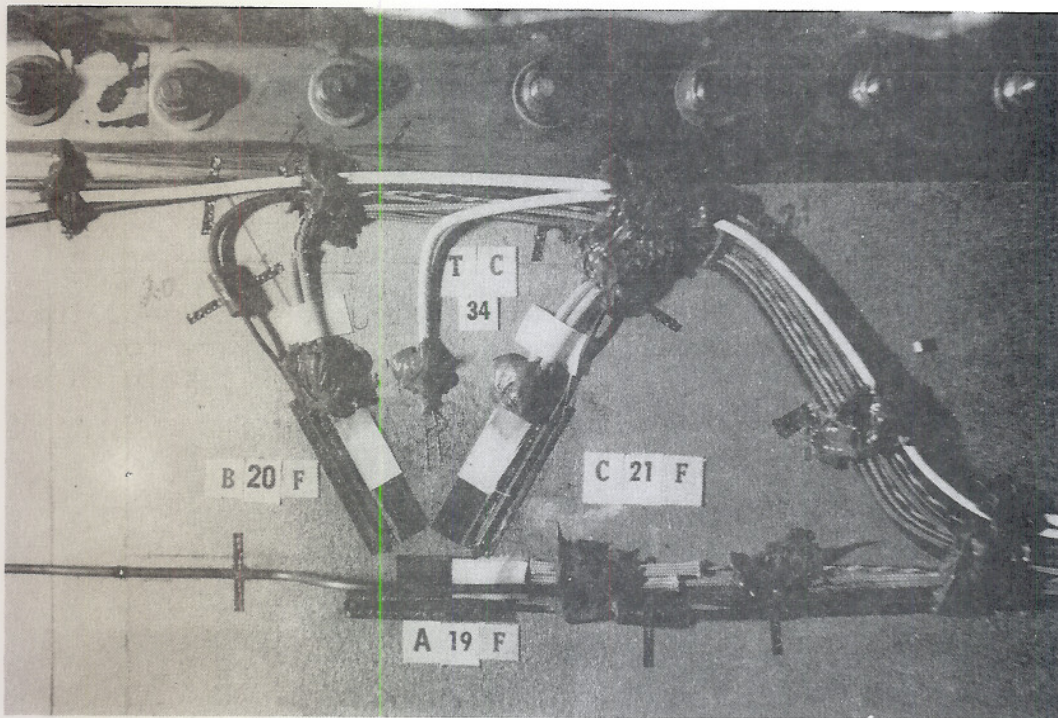


Figure 2. Strain Gage and Thermocouple Installation.

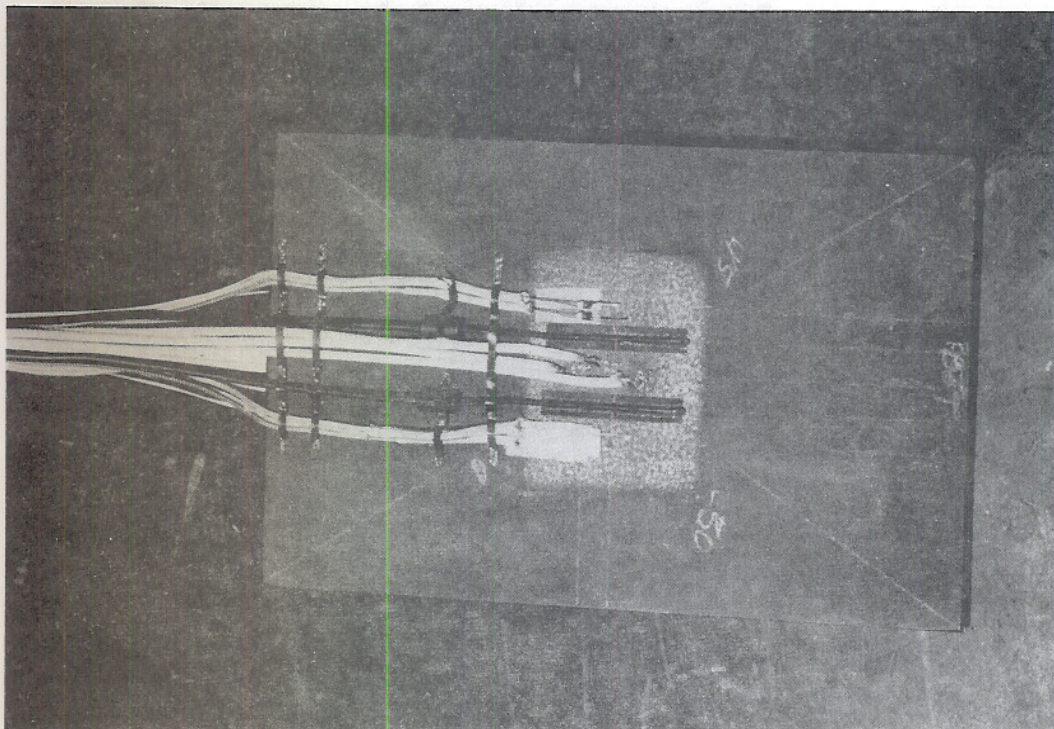


Figure 3. Apparent Strain Test Specimen.

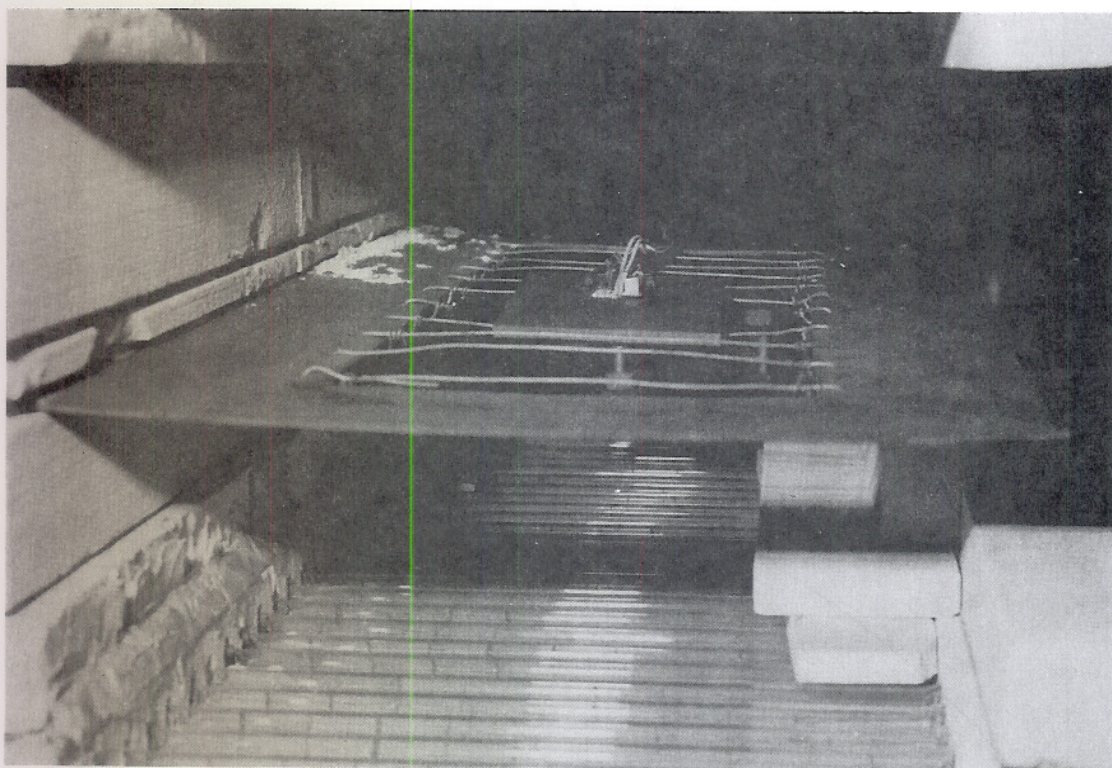


Figure 4. Apparent Strain Test Fixture.

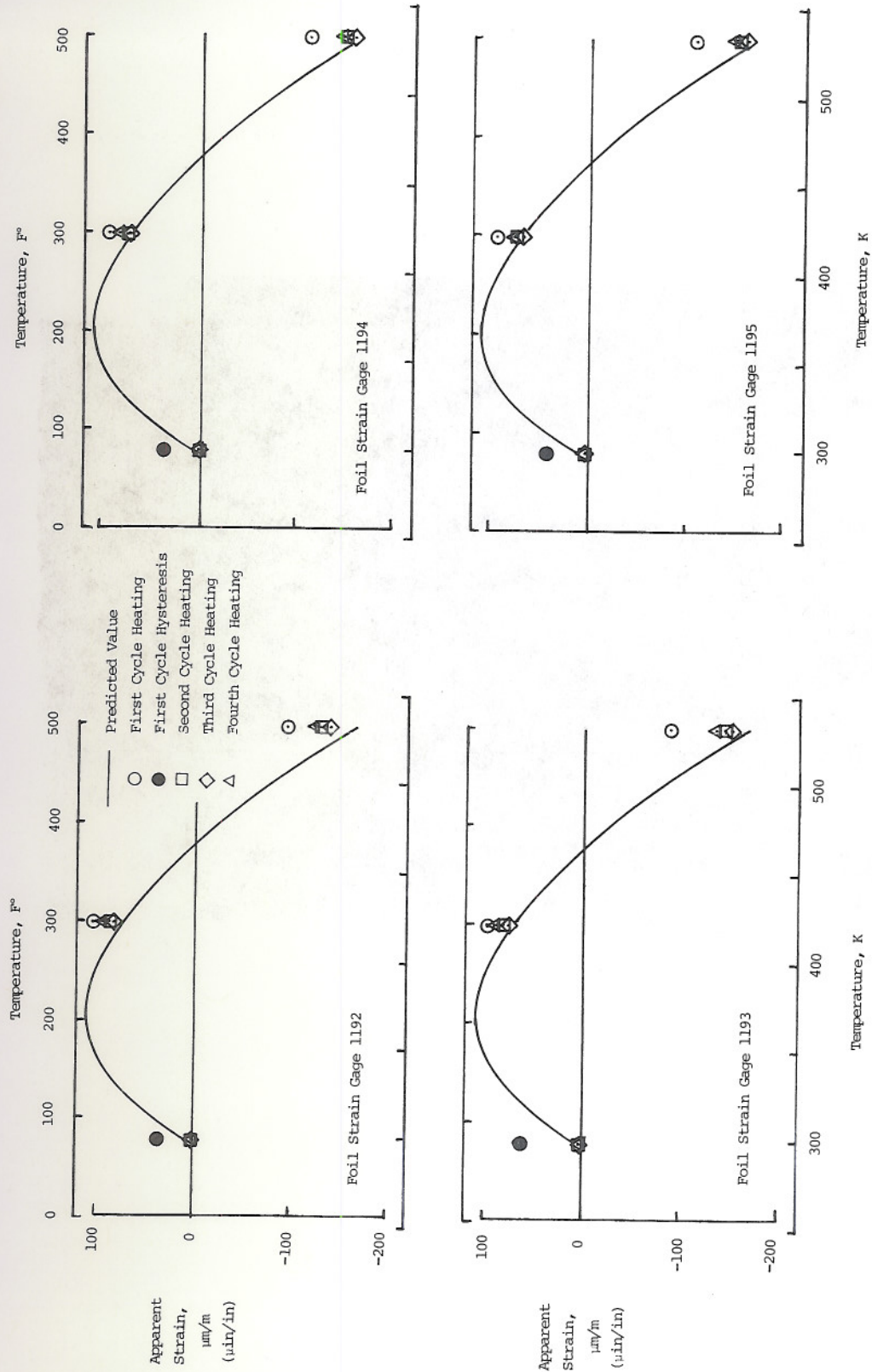


Figure 5. Comparison of Predicted and Measured Apparent Strain for Eight Foil Strain Gages.

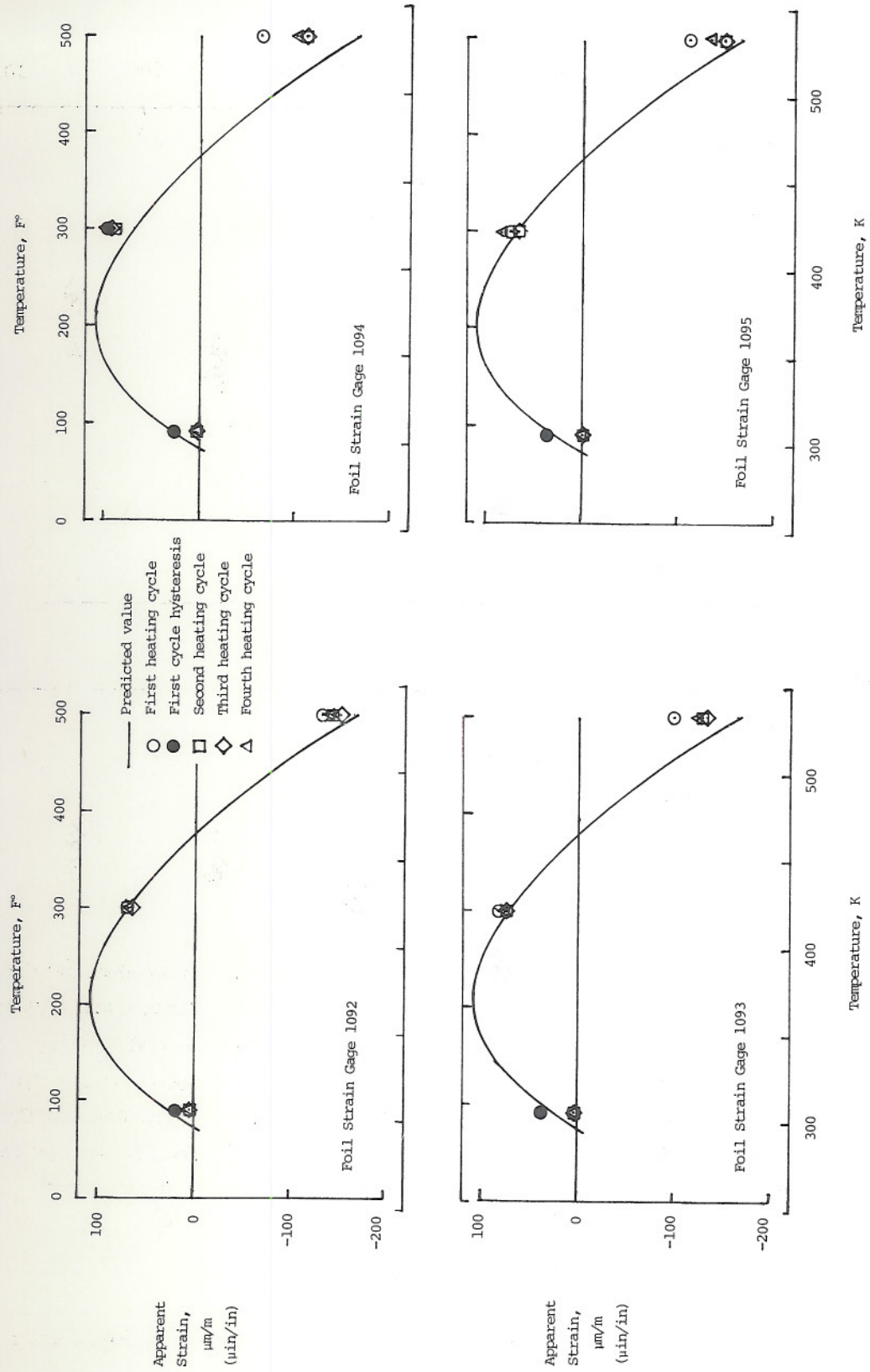


Figure 5. Concluded.

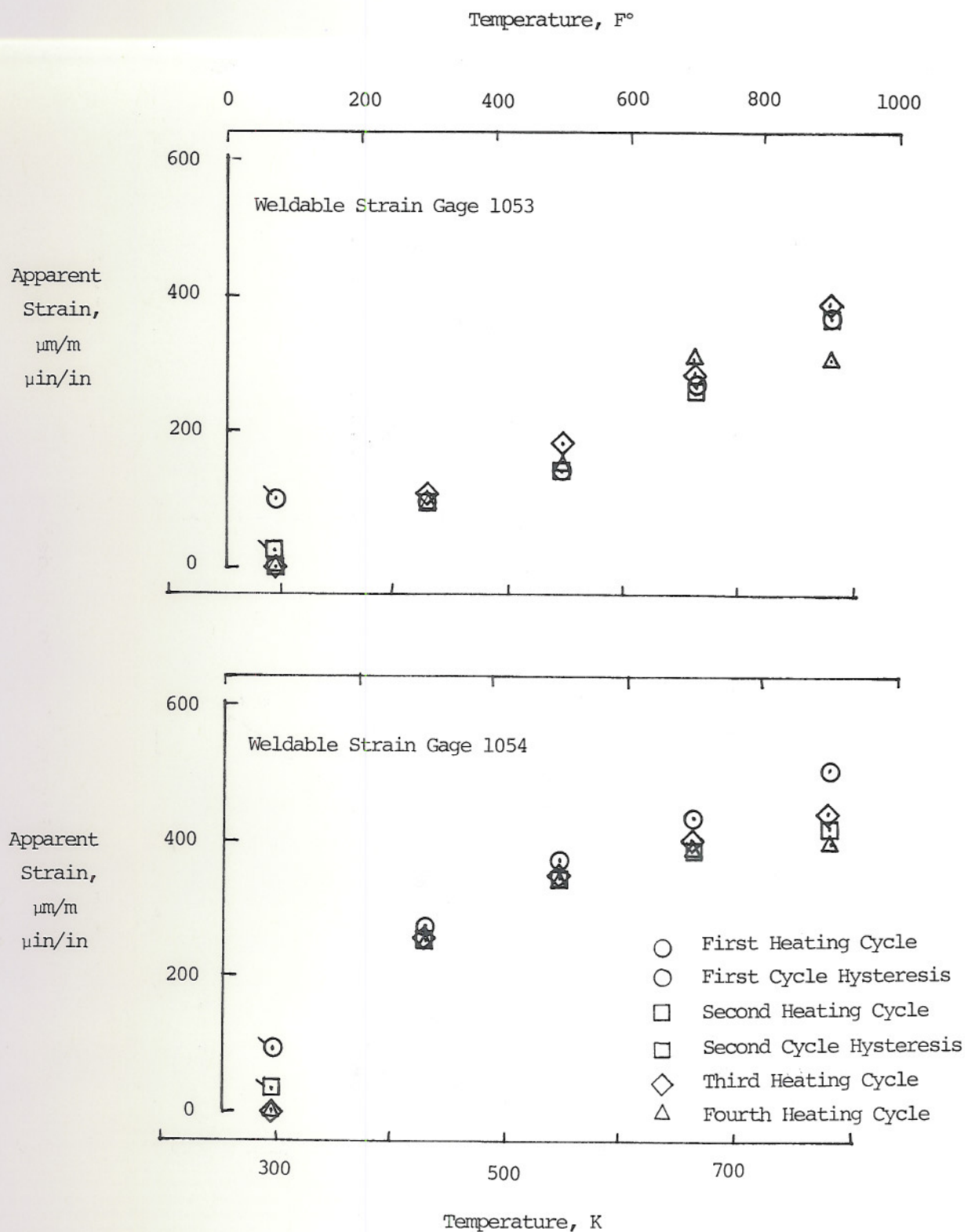


Figure 6. Measured Apparent Strain for Seven Weldable Strain Gages.

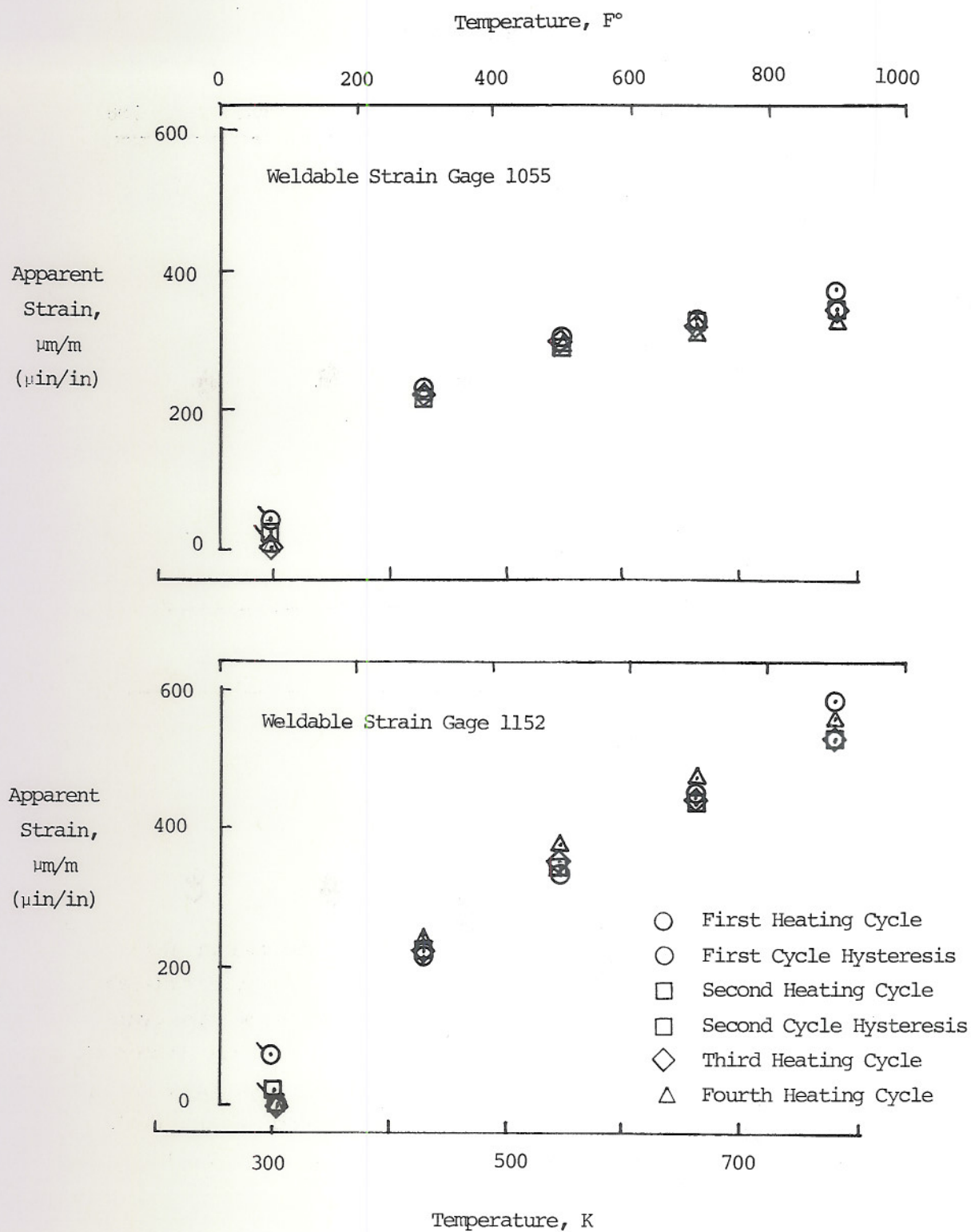


Figure 6. Continued.

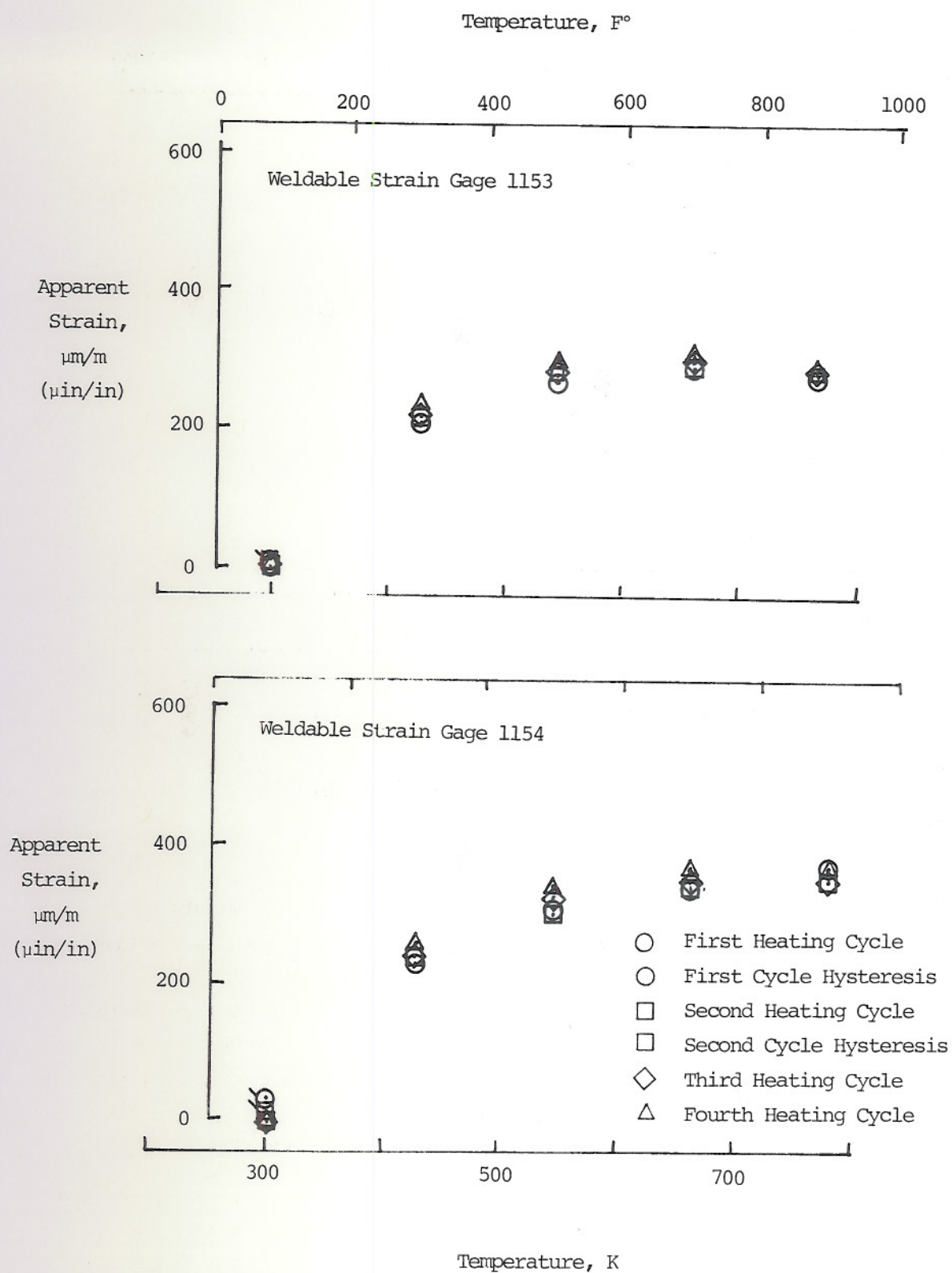


Figure 6. Continued.

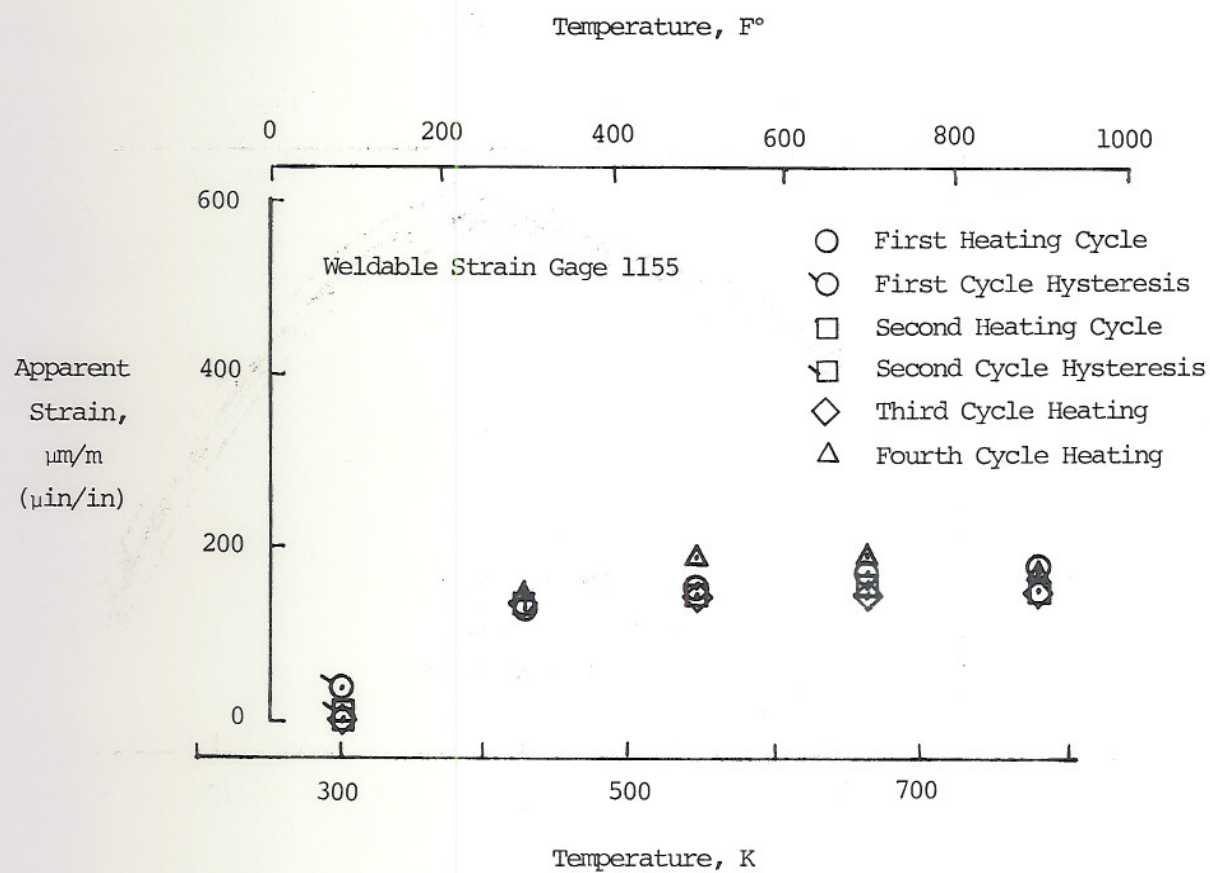


Figure 6. Concluded.

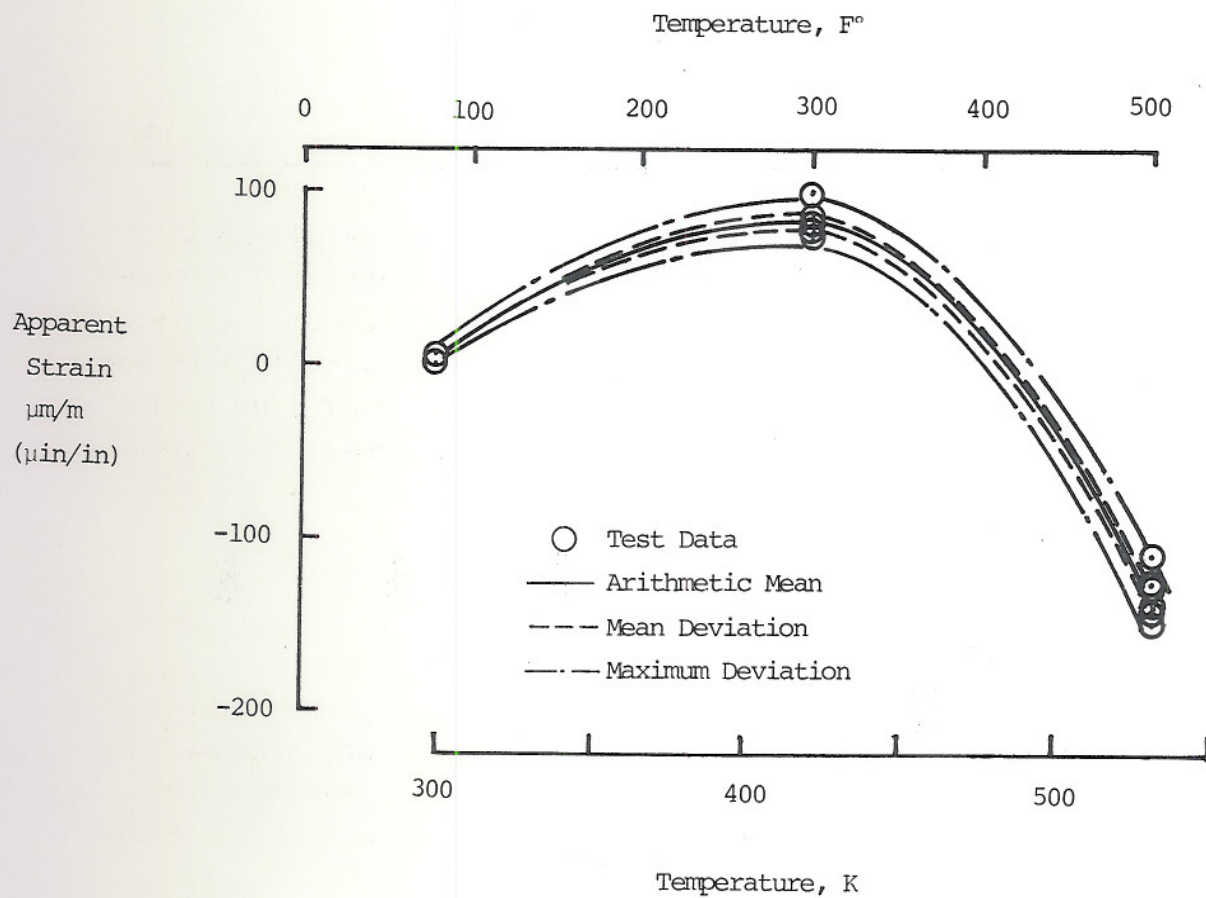


Figure 7. Summary of Measured Apparent Strain for Eight Foil Strain Gages.

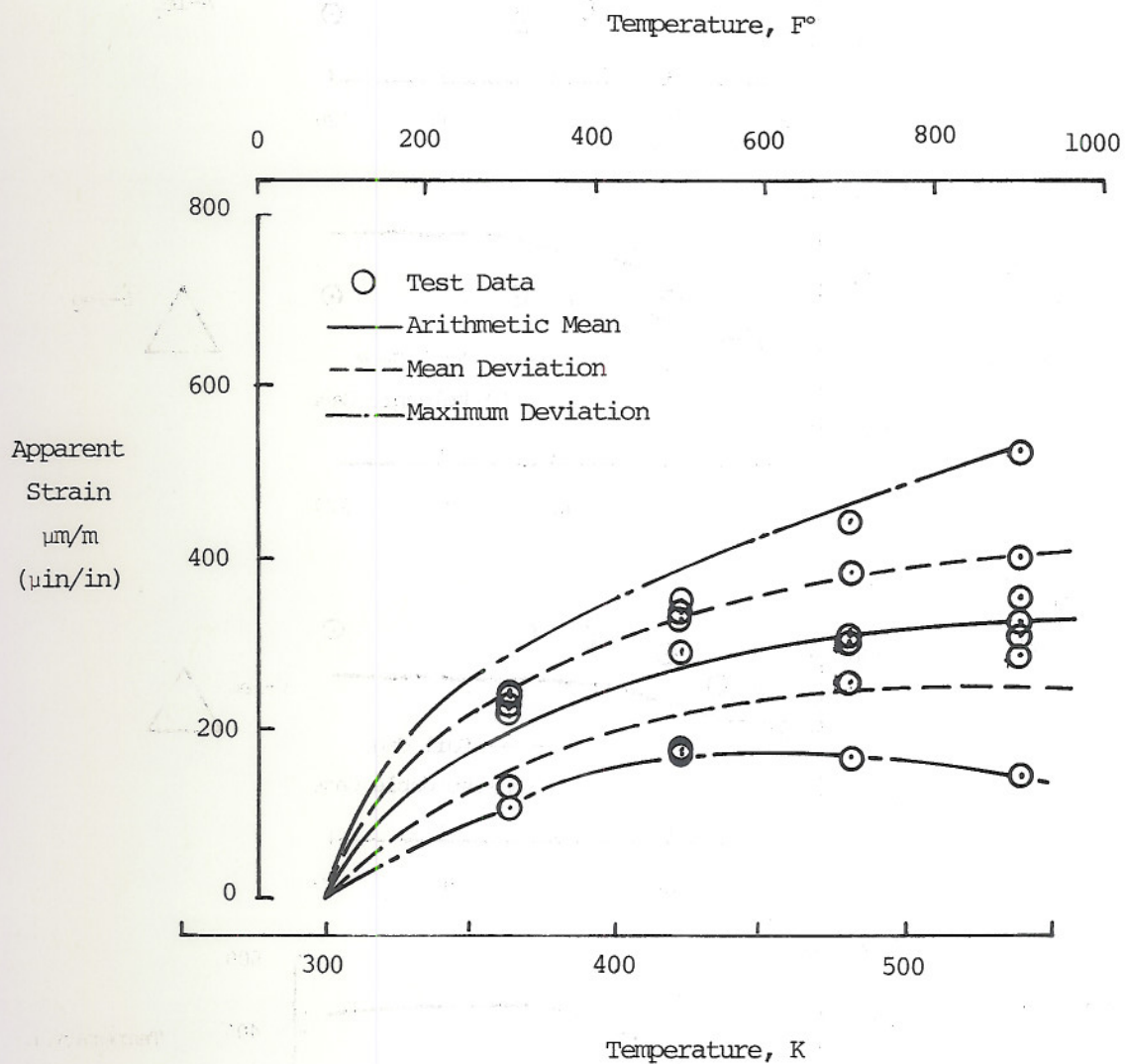


Figure 8. Summary of Measured Apparent Strain for Seven Weldable Strain Gages.

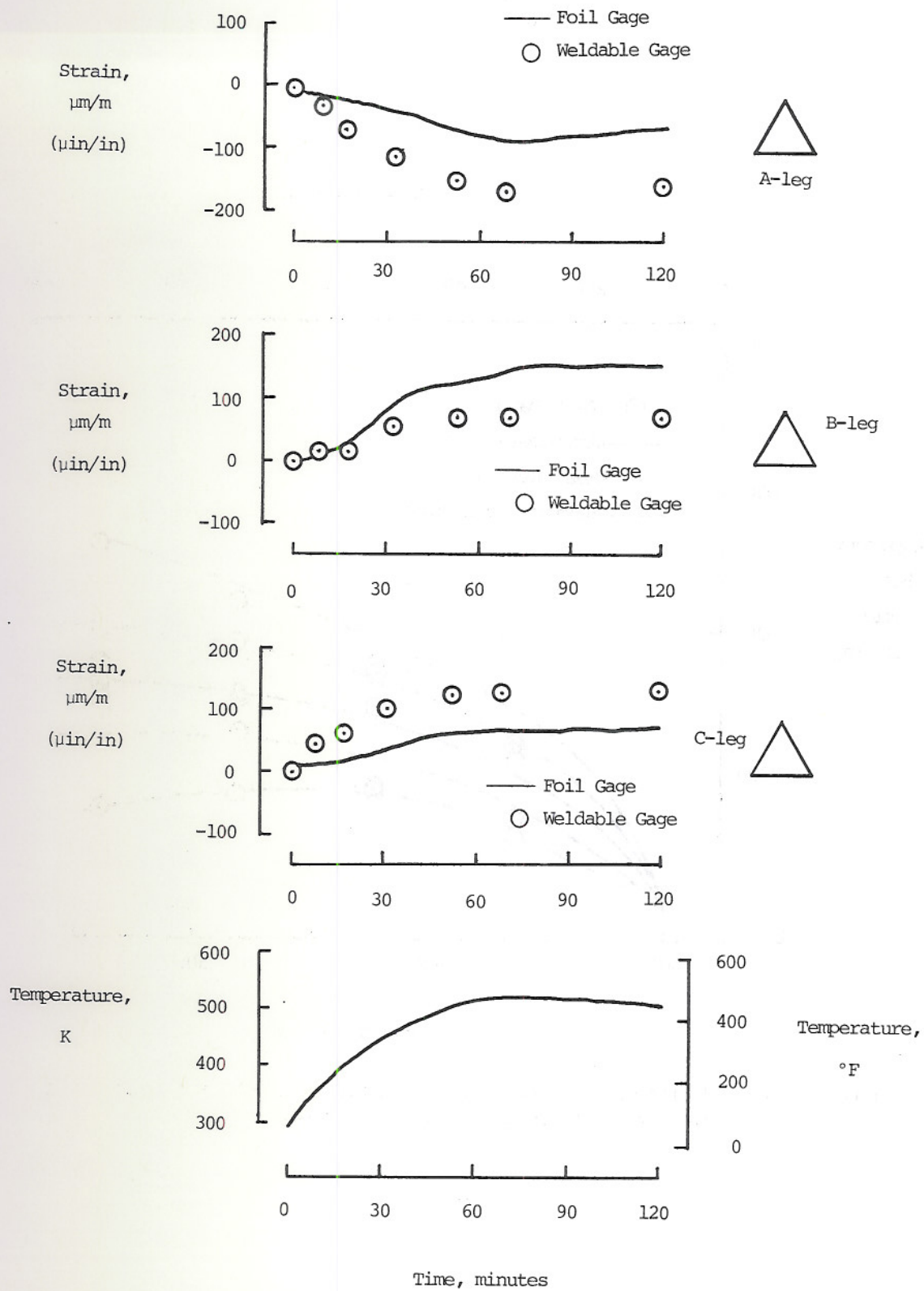


Figure 9. Time-history of Temperature and Strains for the Strain Gage Rosettes.

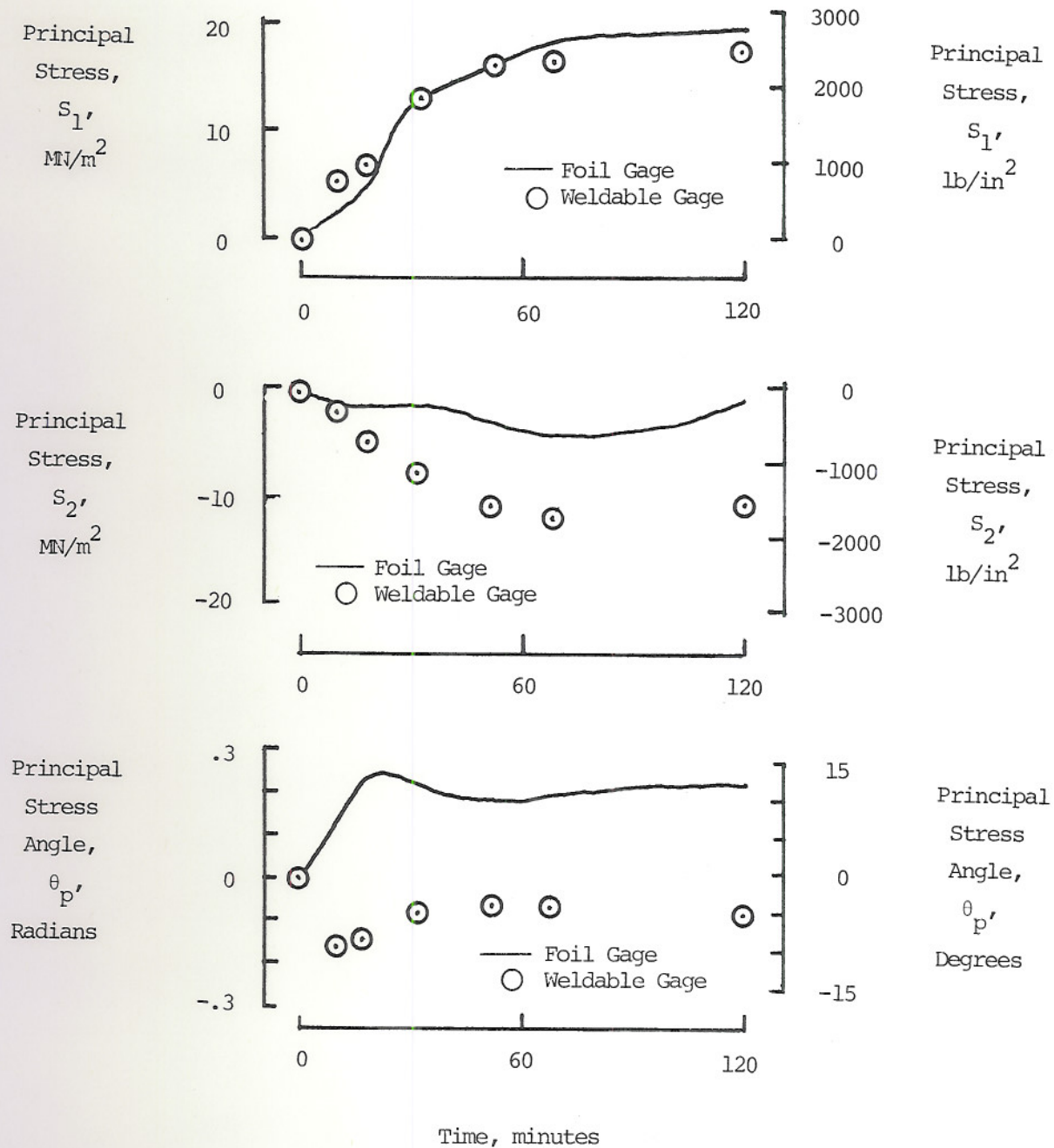


Figure 10. Time-history of Principal Stresses and Principal Stress Angles.

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